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PHYSICS OF FLARES: ANALYSIS OF SIMULTANEOUS  
 $H_{\alpha}$  AND X-RAY OBSERVATIONS

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20. ABSTRACT (Continue on reverse side if necessary and identify by block number) The results of flare research supported by this contract are reviewed. From analyses of optical, X-ray and microwave observations, significant results bearing on the physics of flares were obtained in three areas: (1) flash phase of flares, (2) thermal -			

phase of flares, (3) magnetic field configuration and reconnection in flares. We have found evidence that the energy release in flares occurs in a localized region over the magnetic inversion line, typically involves the eruption of a filament, and often is accomplished through magnetic field reconnection. We have also found evidence that the mass of the thermal X-ray plasma is supplied mainly by conduction-driven evaporation rather than by explosive evaporation of the chromosphere by the impulsive high-energy electrons; these electrons are apparently inhibited from streaming directly to the chromosphere. Our results demonstrate the power of combined analysis of simultaneous high-resolution visible, microwave and X-ray observations for probing the physics of flares. With support from our continuing AFGL contract, we plan to further probe the physics of flares through analysis of many additional flares with high quality simultaneous optical, microwave and X-ray observations which will be obtained over the next few years through the maximum of the present cycle of solar activity.

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## I. INTRODUCTION

For the past several years, the Caltech Solar Astronomy Group has been actively engaged in the observation of solar flares, both in the visible at Big Bear Solar Observatory (BBSO) and in microwaves at Caltech's Owens Valley Radio Observatory (OVRO) and at the NRAO Very Large Array (VLA) in New Mexico. For many of the flares observed at BBSO, there have been simultaneous X-ray observations from spacecraft. The BBSO optical observations show the pattern and structure of the magnetic field in the flare region, the location of the low-temperature components of the flare within this structure, the spectrum of the visible emission, and the presence and character of mass motions. The X-ray and microwave observations reveal the impulsive high-energy electrons and the high-temperature coronal plasma in flares.

The purpose of our AFGL contract was to support research on the physics of flares based on the analysis of observed flares, specifically those for which there were BBSO optical observations with simultaneous X-ray and/or microwave observations. The research carried out with support from this contract falls into the following three categories:

1. Flash phase of flares.
2. Thermal phase of flares.
3. Magnetic field configuration and reconnection in flares.

As will be presented below, significant results were obtained in each of these areas.

## II. RESULTS

### A. Flash Phase of Flares

Zirin (1978a) studied the flash phase of more than 50 flares by carefully comparing BBSO H $\alpha$  movies with simultaneous hard (photon energy  $\gtrsim 20$  keV) and soft (photon energy  $\approx 5$  keV) X-ray

data from OSO-7, OSO-5, OGO-5 and ESRO TD-1A. These data were supplemented by microwave radio observations and by BBSO 3835 Å filtergram movies. The principle conclusions from this study are the following:

- (1) In almost all ( $\approx$  95%) flares, there is a perfect correspondence between the rise and peak of the  $H\alpha$  emission and the hard X-ray flux with no time delay.
- (2) Flares having the same soft X-ray peak flux also have the same  $H\alpha$  peak intensity independent of the amount of hard X-ray flux.
- (3) Each spike of a multiple-spike hard X-ray burst corresponds to a new  $H\alpha$  feature, not to repeated brightening of the same feature.
- (4) Flares with hard X-rays always rise more rapidly both in  $H\alpha$  and in soft X-rays than flares with no observable hard X-rays.
- (5) Flares are observed in 3835 Å filtergrams if they have hard X-ray flux greater than 8 photons  $cm^{-2}$   $keV^{-1}$   $sec^{-1}$  in the OSO-7 20-30 keV channel or soft X-ray flux greater than  $5 \times 10^4$  photons  $cm^{-2}$   $keV^{-1}$   $sec^{-1}$  in the OSO-7 5.1-6.6 keV channel. Flares with less intense X-rays produce no observed brightening in 3835 Å filtergrams. This is strong evidence that the low chromospheric network (other than in flares) is not heated by back conduction from the corona.
- (6) Cases of nearly simultaneous growth of  $H\alpha$  emission at distant points indicate that an agent travelling faster than  $5 \times 10^3$   $km$   $sec^{-1}$  is responsible, presumably electrons.
- (7) In numerous cases nearly identical flares occur within hours indicating that the general magnetic field configuration is not destroyed in a flare.
- (8) In all cases in which a flare with hard X-ray emission was observed near the limb, impulsive  $H\alpha$  emission came from an elevated source and had the same time duration as the hard X-ray burst. The elevated  $H\alpha$  source could usually be seen to

be part of an erupting filament. Apparently, the impulsive  $H\alpha$  emission is excited by the same impulsive high-energy electrons which produce the hard X-ray burst.

This last result suggests that in the flash phase, the seat of the flare energy release is located within the erupting filament. Further evidence for this conclusion was pointed out by Zirin and Moore (1978), based on a collection of Big Bear  $H\alpha$  movies of spectacular flares, mainly flares showing dramatic eruptions and mass motions. In particular, many of these flares begin with the eruption of a filament which lies along the neutral line across which the flare occurs. These high resolution movies give the strong impression that the filament eruption is the seat of the basic flare energy release process rather than just a peripheral side effect, so that much of the flare energy in the flash phase may be released within the erupting filament.

In another paper concerning the flash phase of flares, Zirin (1978b) pointed out that the  $Ly\alpha/H\alpha$  intensity ratio is of order unity in quasars, solar flares, and the quiet solar atmosphere. He argues that the low value of this ratio indicates that  $Ly\alpha$  has a very large optical depth, and that the invariance of the ratio for diverse physical situations suggests that both  $H\alpha$  and  $Ly\alpha$  are important in cooling the partially ionized plasma in each case. Apparently, the  $Ly\alpha/H\alpha$  ratio reflects a general property of the chromosphere-corona interface that is independent of the particular mode or strength of the heating.

Zirin (1980) analyzed three flares which were observed in 1978 at Big Bear in photospheric continuum emission as well as in various photospheric and chromospheric lines. The observations showed (1) that the photospheric emission was a blue continuum corresponding to an increase in the temperature of the upper photosphere by several hundred degrees, (2) that the continuum patches were located at the feet of magnetic flare loops visible in  $H\alpha$ , and (3) that the continuum flashes coincided in time with impulsive microwave spikes and impulsive hard X-ray emission. It appears that the impulsive electrons contained enough energy to

power the required heating of the upper photosphere, but it is not known how or whether this energy can be transported to the upper photosphere. Hence, there might be in situ heating of the photosphere at the feet of the flare loops simultaneously with the acceleration of the impulsive electrons at coronal heights.

Marsh, Zirin, Hurford and Hjellming (1978) announced results for five impulsive flares which were observed simultaneously with the VLA microwave interferometer and optically at Big Bear in July, 1978. Analysis of the radio observations by K. Marsh determined the spatial size and heliographic location of the impulsive microwave emitting region. Comparison with the H $\alpha$  pictures showed that in each flare the microwave emission came from a region which was smaller than the overall H $\alpha$  flare and was located over the magnetic inversion line between opposite-polarity emission regions of the H $\alpha$  flare.

Further analysis of these flares, combining the VLA and BBSO data with microwave spectral data from Sagamore Hill, has been completed by Marsh. A comprehensive paper (Marsh, Zirin, Hurford and Hjellming, 1980) giving a full account of the observations and their interpretation in terms of a flare model is nearly completed. The main idea of the model is that the flare is powered by magnetic field reconnection which begins in the chromosphere or very low corona.

## B. Thermal Phase of Flares

Moore was Team Leader of the Thermal Phase Team in the Skylab Solar Workshop on Solar Flares. The Thermal Phase Team was primarily concerned with the physics of the  $T \sim 10^7$  K thermal X-ray plasma in flares. As Team Leader, in addition to coordinating and directly contributing to the Team's research, Moore was responsible for reporting the results of his Team's research in the form of a chapter in the Flare Workshop Monograph (Moore *et al.*, 1979).

The Thermal Phase Team's chapter, "The Thermal X-Ray Flare Plasma", consists of the following five main sections, each of

which is the equivalent of a research journal paper.

1. Background - A review of the knowledge and understanding of the flare thermal X-ray plasma prior to the Workshop; this review was researched and written by R. Moore (1978, BBSO #0174).
2. The System of Post-Flare Loops on July 29, 1973 - A detailed empirical study of the configuration, structure and evolution of the thermal X-ray plasma in this large two-ribbon flare.
3. The Decay Phase of the Flare of September 7, 1973 - A physical analysis of another large two-ribbon flare; this study complements the above study by being based on different types of data and methods of analysis.
4. Compact Flares - Diagnostics and modeling of the thermal X-ray plasma in subflares an order of magnitude smaller in linear extent than the above two large flares.
5. Overview - Summary and comparison of the results of the above three Team Projects: demonstration and interpretation of the results by means of the diagnostic diagram developed by R. Moore for estimating the state of heating and cooling of the thermal X-ray plasma.

The main results found by the Thermal Phase Team in the above studies are the following.

1. The density of the thermal X-ray plasma is roughly an order of magnitude larger in compact flares than in large two-ribbon flares. At flare maximum, the electron density is typically in the range  $10^{11}$ - $10^{12}$  cm $^{-3}$  in compact flares (overall length scale  $L < 10^9$  cm) and in the range  $10^{10}$ - $10^{11}$  cm $^{-3}$  in large flares ( $L \sim 10^{10}$  cm).
2. In large two-ribbon flares there is continued flare energy release and heating of new X-ray plasma far into the decay phase. This heating occurs on progressively higher loops at the leading edge of the growing X-ray arcade and expanding flare ribbons. The heating probably results from magnetic field reconnection at a vertical current sheet which forms in the wake of an

outward eruption in the preflare magnetic field configuration at the onset of the flare.

3. In compact flares, there is probably relatively less continued heating in the decay phase than in large two-ribbon flares.
4. The thermal X-ray plasma cools approximately equally by conduction and by radiation in flares of all sizes.
5. The bulk of the mass of the thermal X-ray plasma is supplied during the rise phase by chromospheric evaporation from the feet of the X-ray loops. Most of this evaporation is probably driven by downward heat conduction from  $T \geq 10^7$  K plasma in the upper portions of the loops. If so, most of the flare energy which goes into the thermal X-ray plasma may go directly into a very high temperature ( $T \sim 10^8$  K) thermal plasma at the top of the flare arch rather than first going into beamed non-thermal electrons which impinge on the chromosphere.

After the Flare Workshop, Moore (1978a) extended his analysis of the energetics of the thermal X-ray plasma to further investigate the mass supply process for this plasma. The basic conclusion is that the bulk of the mass of the thermal X-ray plasma is supplied by conduction-driven evaporation rather than by explosive evaporation by the impulsive electrons impinging on the chromosphere in the flash phase. This implies that the impulsive electrons are not strongly beamed along magnetic field lines down to the chromosphere, i.e., instead of being primarily beamed and non-thermal, the impulsive electrons may be more nearly isotropic and thermal. The evidence for conduction-driven evaporation comes from the evolution of the thermal X-ray plasma in the simple closed-arch model used by Moore in his diagnostic studies, and from the good agreement of the observed evolution with that of the model.

Moore (1978b) also investigated the physical basis for the well-known empirical result that the temperature of the X-ray plasma at flare maximum is virtually always in the narrow range  $1-2 \times 10^7$  K for flares of all sizes. His above work on the energetics and mass supply of the X-ray plasma showed that conduction-driven evaporation

adjusts the temperature and density of the X-ray plasma so that at flare maximum the plasma cools about equally by radiation and conduction. The temperature  $T^*$  at which radiative cooling equals conductive cooling is given by  $T^* \approx 1.3 \times 10^{-3} L^{4/11} (n_e T)^{4/11}$  K. For the length scales  $L$  and plasma pressures  $n_e T$  of the X-ray plasma observed at flare maximum in real flares,  $T^*$  is nearly always in the range  $1-2 \times 10^7$  K. Hence, the reason  $T$  is in this range is that conduction-driven evaporation adjusts  $T \approx T^*$ . Since  $n_e T$  is proportional to the energy density of the X-ray plasma, and since the flare energy almost certainly comes from the preflare magnetic field, the fact that  $T^*$  has a value of  $1-2 \times 10^7$  K apparently reflects the strength and overall length scale (loop length) of the magnetic field in flaring configurations. The fact that  $T^*$  is practically invariant with  $L$  results from an empirical inverse proportionality between  $L$  and  $n_e T$ . This implies that the strength and scale of the preflare magnetic field are inversely correlated.

K. Marsh, H. Zirin and G. Hurford (1979) wrote a paper on a sequence of 3 small flares which were observed with the VLA microwave interferometer in New Mexico. The flares were observed simultaneously at 6 cm with the VLA, at 2.8 cm with the Owens Valley solar interferometer, in  $H\alpha$  from Big Bear, and in soft X-rays from OSO-8. These observations indicate that the flares occurred on closed magnetic arches of about 10 arc sec in length and having a magnetic field strength of about 300 gauss. The radio emission consisted of a thermal component centered on the top of the arches and small impulsive components probably located at the foot-points at one end of the arches.

### C. Magnetic Field Configuration and Reconnection in Flares

In addition to the results of the forthcoming paper by Marsh et al. (1980), we have found evidence for magnetic field reconnection in flares from three other studies of the magnetic field configuration and its changes in flares.

Moore and LaBonte (1979) studied the onset and magnetic field configuration of the 3B flare of July 29, 1973, the largest flare observed from Skylab. Precursor activity and the flare onset were well observed in H $\alpha$  from the BBSO field station in Tel Aviv, Israel. The preflare coverage showed brightening and motion along the neutral line below the filament. This activity became most noticeable during the last 20 minutes before the filament eruption. These observations were combined with AS&E Skylab X-ray pictures before and after the filament eruption to infer the preflare magnetic field configuration, what happened in this configuration to cause the filament to erupt, and how the magnetic configuration changed in the eruption.

The observations gave the following empirical results.

1. The eruption of the filament and the onset of the two-ribbon H $\alpha$  flare were preceded by precursor activity in the form of small H $\alpha$  brightenings and mass motion along the neutral line and well below the bottom edge of the filament.
2. The onset of the H $\alpha$  flare ribbons occurred simultaneously with the filament eruption; one of the ribbons grew out of a small area which brightened in the precursor activity.
3. The distance of the H $\alpha$  ribbons from the neutral line was initially much less than the height of the filament above the chromosphere.
4. The precursor brightenings and the first brightenings in the flare ribbons were in the vicinity of the steepest magnetic field gradient in the flare region.
5. The magnetic field in the chromosphere and in the filament was greatly sheared across the neutral line, i.e., crossed the neutral line at a small angle.
6. There was no evidence for emerging magnetic flux in the flare region.
7. Prior to the eruption, the filament was under an arcade of closed field lines; a similar closed magnetic arcade was present in the flare after the filament erupted.

These results are interpreted as follows with regard to the magnetic field configuration and its change in the flare.

1. The preflare magnetic configuration was similar to that proposed by Heyvaerts *et al.* (1977, *Astrophys. J.* 216, 123), except that there is no emerging flux. Basically, the magnetic field near the neutral line and supporting the filament is highly sheared, and the amount of shear decreases with distance from the neutral line, so that the highly sheared field is enclosed in an arcade of loops of much lower shear.
2. Both the destabilization of the filament and the initial flare ribbons resulted from magnetic reconnection below the filament.
3. The reconnection began in the region of greatest shear in the magnetic field.
4. Following the initial reconnection which started the eruption, the filament eruption set up the magnetic field configuration for the two-ribbon flare in the manner proposed by Hirayama (1974, *Solar Phys.* 34, 323) and by Kopp and Pneuman (1976, *Solar Phys.* 50, 85), i.e., the filament eruption "opened" the overlying closed magnetic field lines, which then reclosed by reconnection in the wake of the expelled filament.

Kahler, Webb and Moore (1980) have nearly completed a paper on another flare showing evidence for reconnection. Observational results are presented for the magnetic field configuration and its change in a large-scale ( $\sim 10^5$  km) subflare involving a filament disruption and disappearance which occurred on August 29, 1973. This event was well observed both in sequences of X-ray filtergrams from the AS&E experiment on Skylab and in an  $H\alpha$  filtergram movie from BBSO. These observations give evidence for both the preflare and postflare magnetic field configurations, from which we conclude that the flare was produced by large-scale reconnection between two closed bipolar field systems. This conclusion is based on the following specific observational results. (1) The flare was apparently a consequence of a new active region emerging and expanding into an old active region. The flare involved two magnetic

inversion lines: one under the disrupted filament in the old active region and the other between the old region and the advancing new region. (2) The filament appeared to turn over and disappear in place without being ejected from the region. (3) The flare was a "4-ribbon" flare: each of the two inversion lines was straddled by a set of X-ray flare loops rooted in a conjugate pair of  $H\alpha$  flare ribbons. (4) The preflare structure of the flare region indicates that the old-region flux which is observed connected to the new region after the flare was connected across the old inversion line before the flare. The reconnection required to produce the observed postflare configuration from the probable preflare configuration would reduce the shear in the magnetic field across the old inversion line and could disrupt the filament without ejecting it.

Marsh (1978) also found evidence for reconnection in a study of flares in ephemeral active regions. The X-ray bright-point flares discovered with the AS&E X-ray telescope on Skylab are apparently a subset of the ephemeral region flares which can be detected on BBSO  $H\alpha$  films. Marsh has found that these tiny flares usually occur at the periphery of the ephemeral bipolar magnetic region and so may well represent reconnection of the ephemeral region magnetic field with the surrounding network field. If so, ephemeral regions may provide an important contribution to the diffusion of the network field, in addition to that provided by the supergranulation flow.

### III. CONCLUSION

The above results demonstrate the power of combined analysis of simultaneous high-resolution visible, microwave and X-ray observations for probing the physics of flares. Specifically, our studies have indicated that the energy release in flares occurs in a localized region over a magnetic inversion line, typically involves the eruption of a filament, and often, perhaps always, is accomplished through magnetic field reconnection. We have also found evidence

that the impulsive high-energy electrons generated in the flash phase are inhibited from streaming directly to the chromosphere, so that the mass of the thermal X-ray plasma is supplied mainly by conduction-driven evaporation rather than by explosive evaporation of the chromosphere by nonthermal electron beams.

Due to the great diversity of scale, structure and power of solar flares, our present conclusions must still be regarded as tentative. We look forward to testing these conclusions and further probing the physics of flares through analysis of the large number of flares with high quality simultaneous optical, radio and X-ray observations which will be obtained during the present maximum of solar activity. This research will be supported by our continuing AFGL contract.

Scientific Papers and Publications Resulting from Research Supported  
by this Contract:

Marsh (1978): "Ephemeral Region Flares and Diffusion of the Network,"  
Solar Phys. 59, 105.

Marsh, Hurford, Zirin (with R.M. Hjelling of NRAO) (1978): "High  
Resolution Radio and Optical Observations of Solar Flares", paper  
presented at the AAS Solar Physics Div. Meeting, Nov., 1978.

Marsh, Zirin and Hurford (1979): "VLA Observations of Solar Flares,  
Interpreted with Optical, X-Ray and Other Microwave Data", Ap. J.  
228, 610.

Marsh, Zirin, Hurford (with R.M. Hjellming of NRAO) (1980): "VLA  
Observations of Impulsive Flares at 4.9 GHz," in preparation, to be  
submitted to Ap. J.

Moore (1978a): "Evidence that the Mass of the Thermal X-Ray Plasma  
in Solar Flares is Supplied by Conduction-Driven Evaporation", BAAS  
10, 442.

Moore (1978b): "The Temperature of the Thermal X-Ray Flare Plasma,  
Conduction-Driven Evaporation, and the Strength and Scale of Preflare  
Magnetic Fields", paper presented at the AAS Solar Physics Div.  
Meeting, Nov., 1978.

Moore (with B.J. LaBonte of Hale Observatories) (1979): "The Filament  
Eruption in the 3B Flare of July 29, 1973: Onset and Magnetic Field  
Configuration", in Proceedings of IAU Symp. No. 91.

Moore (first author, with the 15 other members of the Thermal Phase  
Team) (1979): "The Thermal X-Ray Flare Plasma", in P.A. Sturrock (ed.),  
Solar Flares: A Monograph from Skylab Solar Workshop II, Colorado  
Associated University Press, Boulder.

Moore (with S.W. Kahler and D.F. Webb of AS&E) (1980): "X-Ray and H $\alpha$  Observations of a Filament-Disappearance Flare: An Empirical Analysis of the Magnetic Field Configuration", in preparation, to be submitted to Solar Phys.

Zirin (1978a): "Studies of Solar Flares, Using Optical, X-Ray and Radio Data", Solar Phys. 58, 95.

Zirin (1978b): "The Ly $\alpha$ /H $\alpha$  Ratio in Solar Flares, Quasars and the Chromosphere", Ap. J. 222, L105.

Zirin (1980): "Three Flares with Blue Continuum, One with a D3 Preflare Shell", Ap. J. 235, in press.

Zirin and Moore (1978): "Filaments and Flares", presented at the AAS Solar Physics Div. Meeting, Nov., 1978.